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ORIGINAL PAPER

UNIVERSAL MODEL FORMS FOR PREDICTING THE DYNAMIC PROPERTIES OF GRANULAR SOILS

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ABSTRACT

Dynamic soil properties are important parameters for the design of structures subjected to various dynamic/cyclic loading such as earthquake which can be obtained by *in situ* and laboratory measurements. Numerous empirical and mathematical models have been proposed to predict the dynamic properties of soils, including maximum shear modulus (G_{max}), normalized shear modulus (G/G_{max} - γ) curve, reference shear strain (γ_r), minimum damping ratio (D_{min}) and damping ratio (D - γ) curve. However, the majority of the existing models were proposed for specific soil types, loading characteristics, initial soil fabrics and strain ranges. This paper proposes five universal models to estimate the G_{max}, γ_r and D_{min} values, and also $G/G_{max} - \gamma$ and $D - \gamma$ curves using a database that contains 117 tests on 5 different granular soils. The proposed models include the effect of grading characteristics, void ratio, mean effective confining pressure, consolidation stress ratio (K_C) and specimen preparation method. The models are validated using experimental data from previous studies for granular soils. The results indicate that the proposed models are capable of evaluating the dynamic properties of granular soil.

1. INTRODUCTION

It is generally recognized that local soil properties affect the ground response when seismic waves propagate through a soil profile. Advances in earthquake ground response analyses which includes predicting the dynamic response of a structure at the geotechnical site have greatly surpassed the knowledge of the basic dynamic soil properties. Some of the most important ground motion parameters are amplitude of motion, frequency content and duration. These parameters are primarily affected by some factors i.e. source effects or the characteristics of the earthquake, path effects, and site effects. A proper understanding of the site response is a key consideration in the solution of earthquake engineering problems. In this regard, laboratory element testing that can mimic field loading conditions plays an important role in understanding dynamic behaviour of soil layers or site effect. The shear modulus (G) and damping ratio (D) are two variable properties of soils are important strain-dependent parameters in estimation of seismic response of a site. Measurements of the shear modulus and damping ratio can be obtained from either laboratory or field tests. Shear modulus at small strains where soils exhibit linear elastic behavior is referred to as small-strain shear modulus, G_{max} or G_o and material damping ratio is referred to as small-strain or minimum material damping ratio, D_{min}. The nonlinearity in the stress-strain relationship results in a decrease in the shear modulus with increasing shear strain amplitude and an increase in energy dissipation and therefore an increase in material damping ratio.

The effect of mean effective confining pressure and void ratio on G_{max} of granular soil has been documented by various investigators (e.g. Hardin and Drnevich, 1972; Stokoe et al., 1999; Gu et al., 2015; Payan et al., 2016). The results indicate that G_{max} increases with increasing mean effective confining pressure and decreases with increasing void ratio. The previous study suggested that shear strain level, void ratio, mean effective confining pressure, grain size distribution characteristics, drainage conditions, stress and fabric anisotropies, shape of particles and loading frequency are important effective parameters on the dynamic properties of granular soils (e.g. Wichtmann et al., 2015; Payan et al., 2016; Chen et al., 2018; Bayat and Ghalandarzadeh, 2018 and 2019). Other parameters have less important effect.

So far, various analytical and empirical models to predict the dynamic properties of granular soils have been proposed (Hardin and Drnevich, 1972; Darendeli 2001; Zhang et al., 2005; Amir-Faryar et al., 2017). The hyperbolic model proposed by Hardin and Drnevich (1972) has been widely used to describe nonlinear soil behavior under dynamic loading. In the proposed hyperbolic model, only one curve-fitting variable (i.e. reference shear strain, γ_r) is involved which results in the model having a poor fit to test data. Using modified hyperbolic models which include a curvature coefficient, such as the model suggested by

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Stokoe et al. (1999), Darendeli (2001) and Zhang et al. (2005) results in significantly improved fits to the data. However, few studies have been conducted on the parameters of the modified hyperbolic models. Darendeli (2001) introduced a reference strain which was different from Hardin and Drnevich's reference strain at which the shear modulus reduces to half of its maximum value. This modified hyperbolic model was later verified for sandy and gravelly soils by Menq (2003). The results indicate that G/G_{max} - γ curve of granular soils is a function of uniformity coefficient (C_u) and mean effective confining pressure (σ'_m). Recent studies indicate that increasing the C_u of granular soils leads to more nonlinear shape of the $G/G_{max} - \gamma$ curves (e.g., Menq, 2003; Anastasiadis et al., 2011; Wichtmann et al., 2011; Senetakis, 2011). However, this trend was not observed in some of previous studies (e.g., Seed and Idriss, 1970; Seed et al., 1986; Rollins et al., 1998). Anastasiadis et al. (2011) and Senetakis (2011) indicated that the poorly graded sands generally have a more linear behavior in comparison to the poorly graded gravels. The results also indicated that the mean grain size (d_{50}) affects the $G/G_{max} - \gamma$ and D - γ curves. However, this trend was not observed by Menq (2003) and Wichtmann et al. (2011). Previous studies indicated that the increase of σ'_m results in more linear behaviour (Menq, 2003; Kokusho et al., 2004; Xenaki and Athanasopoulos 2008; Anastasiadis et al., 2011; Jafarian et al., 2014; Araei and Ghodrati, 2017). Also, previous studies showed that with the increase of mean effective confining pressure and relative density, damping ratio tends to decrease for all shear strain levels (e.g. Chen et al., 2018; Bayat and Ghalandarzadeh, 2018). Although many studies have been done on the dynamic properties of granular soils over the past 50 years, only a few studies (e.g., Payan et al., 2016; Zhou et al., 2017; Chen et al., 2018; Bayat and Ghalandarzadeh, 2019) have considered the effect of inherent and induced anisotropies on the dynamic properties of granular soils. Zhou et al. (2017) and Bayat and Ghalandarzadeh (2020) studied the effects of initial static shear stress on the dynamic properties of granular materials. The results show that the values of G/G_{max} increase with an increasing initial static stress. Bayat and Ghalandarzadeh (2019) studied the effects of initial fabric on the dynamic properties of granular soils. Based on the results, it can be concluded that the effect of initial fabric on D is more pronounced than on G/G_{max} and also this effect seems to be independent of soil type.

The current study presents the results of a series of cyclic triaxial, resonant column and bender element tests for granular materials in a wide shear strain range from the orders of 10^{-6}–10^{-2}, and the effects of mean confining pressure, void ratio, grading characteristics and inherent and induced anisotropies on the dynamic properties are evaluated. Modified models are developed to accurately characterize the G_{max}, γ_r, D_{min} and also $G/G_{max} - \gamma$ and $D - \gamma$ curves. Using the experimental data, the applicability of the models is assessed in the estimation of the dynamic properties of granular soils.

2. DATABASE

The existing laboratory data used in the current study are compiled from the author's published works. Table 1 summarizes the sources of data used in this study that include bender element, resonant column and cyclic triaxial tests. In this paper, the shear modulus and damping ratio of specimens at the medium to large shear strain range (shear strain ranging from 10-4 and 10-2) were extracted from the results of cyclic triaxial testing and the results of resonant column test were used to derive the dynamic properties at small to medium shear strain amplitudes (approximately between 10-6 and 10-4). Bender element was used to monitor the small strain shear modulus at very small strain amplitudes ($\gamma \leq$ 10-5). Test apparatus, materials properties and testing procedure are presented in summary in the following section. More details can be found in Bayat and Ghalandarzadeh (2018, 2019 and 2020).

3. TEST APPARATUS, MATERIALS AND TESTING PROCEDURE

3.1. TEST APPARATUS

As mentioned in the previous section, bender element, resonant column and cyclic triaxial

Table 1 Summary of the sources of data used in the current study.

Test Group	Variables	σ'_m (kPa)	$K = \frac{\sigma'_1}{\sigma'_a}$	Dr (%)	Depositional method	No. of tests	References
Group-1	σ'_m, Dr and Grading characteristics	100, 300 and 600	1	10, 30 and 60	WT	45	Bayat and Ghalandarzdeh (2018)
Group-2	σ'_m, Dr, Grading characteristics and K	267, 280, 300, 333 and 400	0.5, 0.75, 1, 1.25 and 1.5	10, 30 and 60	WT	51	Bayat and Ghalandarzdeh (2020)
Group-3	σ'_m, Dr, grading characteristics and Depositional method	100, 300 and 600	1	10 and 60	WT, AP and WP	21	Bayat and Ghalandarzdeh (2019)

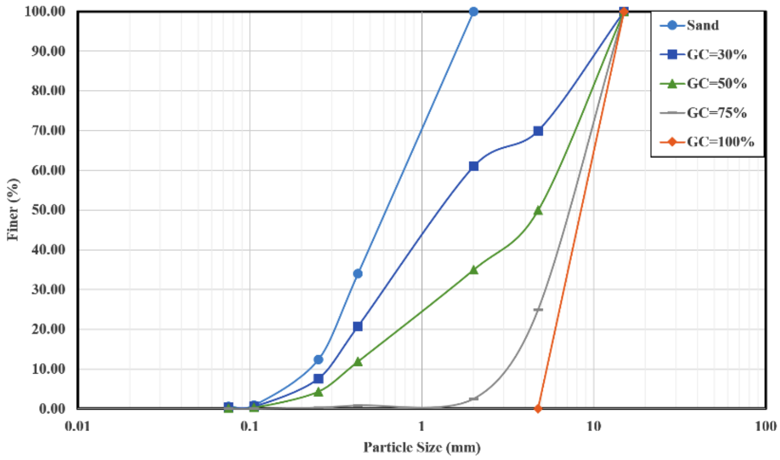

Fig. 1 Grain size distribution curves of the granular soil mixtures.

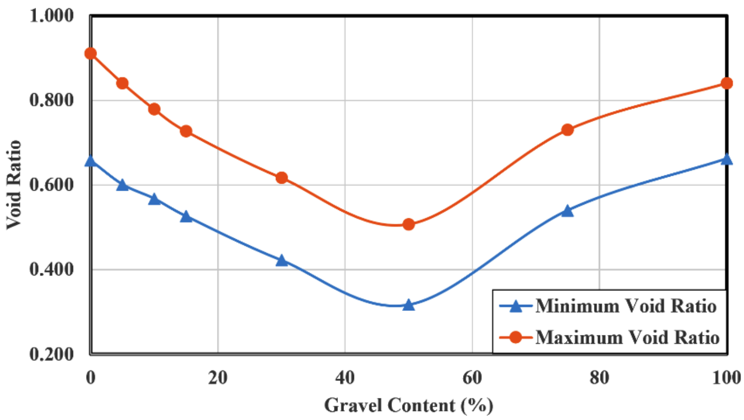

Fig. 2 Maximum and minimum composite void ratios versus gravel content.

apparatuses were used to measure the shear modulus and damping ratio of granular soils. The cyclic triaxial tests were carried out according to the specifications of the ASTM D3999 (2013) to drive the shear modulus and damping ratio at medium to large shear strain amplitudes. In cyclic triaxial testing, a slow axial loading was applied at the top of the specimen. Axial strain was measured by two LVDTs (linear variable differential transducers) placed at opposite on the triaxial specimen. Based on the stress and displacement at the top of the specimen, hysteresis loops are generated. The shear modulus for each cycle of loading is evaluated by calculating the slope of the line that connects the end points of the hysteresis loop. Damping ratio is evaluated by calculating the ratio of the area within the hysteresis loop and the maximum potential energy stored in each cycle of motion as represented by the triangular area. A pair of bender elements (i.e. a transmitter and a receiver) was implemented in the triaxial cell to determine the shear wave velocity (V_S). The first major deflection of the received signal is utilized to determine the shear wave arrival time. The V_S is measured and the very small shear strain modulus, G_{max}, is calculated ($G_{max} = \rho . V_S^2$). The shear modulus and damping ratio of the specimens at small shear strains was measured using a free-free resonant column apparatus. The free-vibration decay (FVD) method was used for damping derivation. The bender element, resonant column and cyclic triaxial tests were combined in order to determine the normalized shear modulus degradation and damping curves of the granular specimens.

3.2. MATERIAL AND TESTING PROCEDURE

Five gradations of granular material were used to study the influence of grading characteristics, relative density, mean effective stress, inherent and induced anisotropies on the dynamic properties. The pure sand and gravel were clean, uniformly-graded that was classified as *SP* and *GP* according to the unified soil classification system (USCS), respectively. Each subgroup of the materials was denoted by the values of the gravel content (*GC*). For example, the gravel content of GC-30 is 30 % by weight. The grain size distribution curves of the materials with varying gravel contents are shown in Figure 1. Table 2 shows grading characteristics of the materials. The maximum and minimum void ratios (e_{max} and e_{min}) versus gravel content are presented in Figure 2. Table 1 summarizes the number of tests carried out on reconstituted specimens with a diameter of 100 mm and a height/diameter ratio equal to 2 which were prepared

Table 2 Grading characteristics of five soil subgroups.

Soil subgroup	d_{50} (mm)	C_u	C_c
GC-0	0.61	3.59	0.88
GC-30	1.15	7.02	1.15
GC-50	4.75	15.39	4.75
GC-75	7.07	2.67	7.07
GC-100	8.30	1.80	8.30

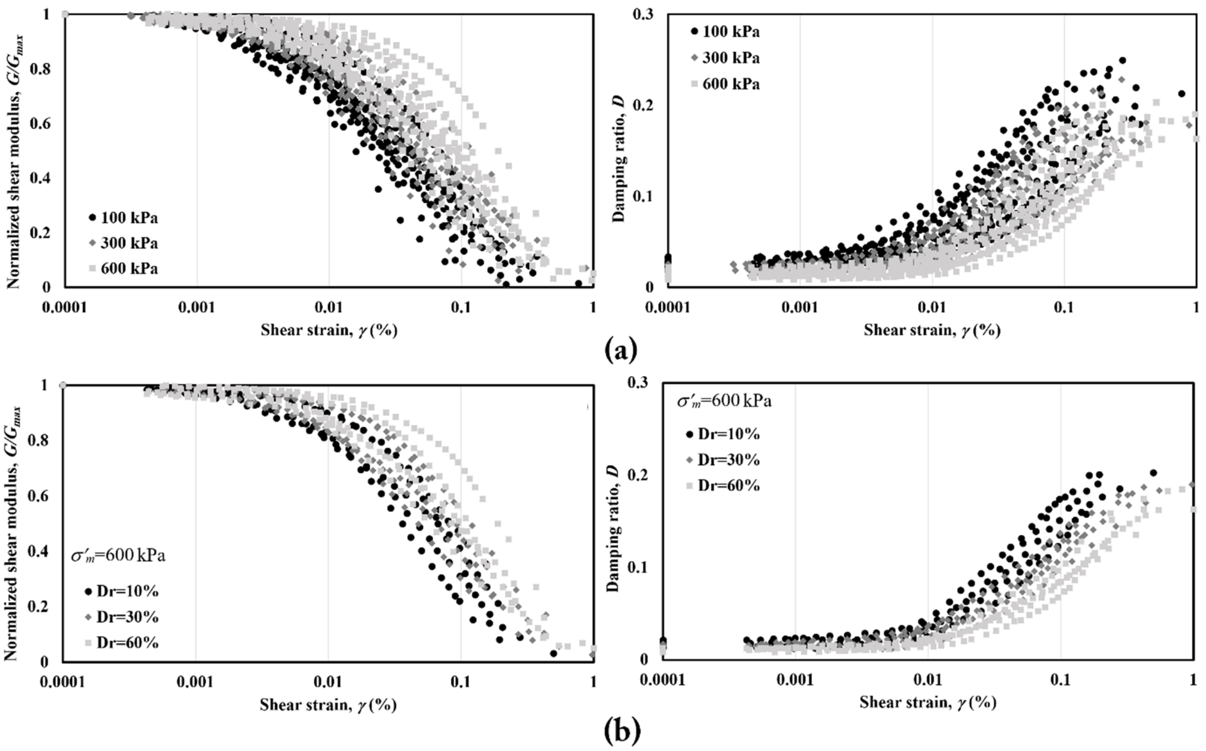

Fig. 3 Variation of G/G_{max} and D as a function of γ in terms of (a) mean effective confining pressure (b) relative density.

by wet tamping (WT), water pluviation (WP) or air pluviation (AP). More details can be found in Bayat and Ghalandarzadeh (2018, 2019 and 2020).

4. TESTS RESULTS AND DISCUSSION

The dynamic properties of the all subgroups of materials (GC - 0, GC - 30, GC - 50, GC - 75 and GC - 100) under isotropic or anisotropic loading conditions were determined from bender element, resonant column and cyclic triaxial testing. Based on the results, the effects of relative density, mean effective stress, grading characteristics, induced anisotropy and deposition method on the dynamic properties were assessed. Note that the tests results presented in section 4 are related to the results of the current study and the author's previous published papers (Bayat and Ghalandarzadeh, 2018, 2019 and 2020).

4.1. EFFECT OF σ'_m AND D_r ON $G/G_{max} - \gamma$ AND $D - \gamma$ CURVES

Group 1 of the tests was performed on the all subgroups under isotropic conditions at different values of D_r and σ'_m. The aim of group 1 testing was to examine the effect of grading characteristics, D_r and σ'_m on dynamic properties. In this group of the tests, the WT method was used with a low initial moisture content and consideration of under-compaction of the lower layers during preparation which has the advantage of easy control of void ratio (Ladd, 1987; Maleki and Bayat, 2012). The results show that the effect of σ'_m on the dynamic properties is more significant than the effect of grading characteristics and D_r. Figure 3(a) shows the effect of σ'_m on $G/G_{max} - \gamma$ and $D - \gamma$ curves for all subgroups at different D_r. As expected, G/G_{max} increased and D decreased as σ'_m increased, especially in the large shear strain region. For example, the effect of D_r on $G/G_{max} - \gamma$ and $D - \gamma$ curves for all subgroups at σ'_m=600 kPa is shown in Figure 3(b). As expected, G/G_{max} increased and D decreased as D_r increased. More details about effects of D_r and σ'_m dynamic properties may be found in Bayat and Ghalandarzadeh (2018).

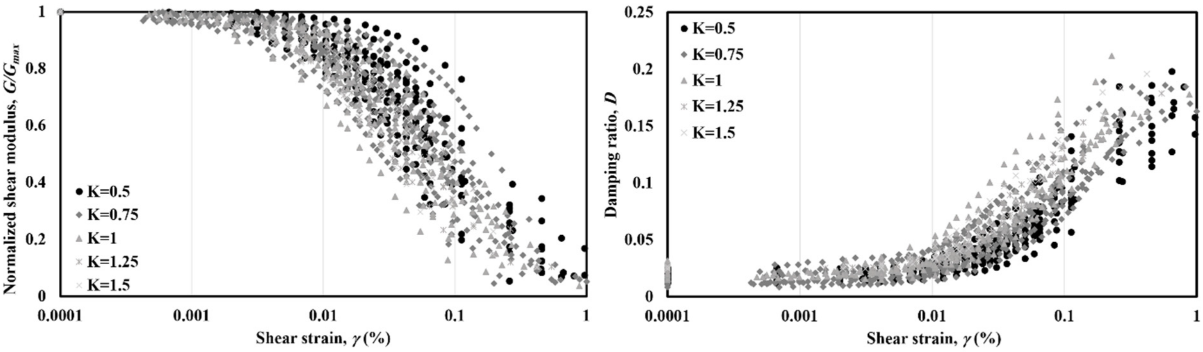

Fig. 4 Variation of G/G_{max} and D as a function of γ in terms of consolidation stress ratio.

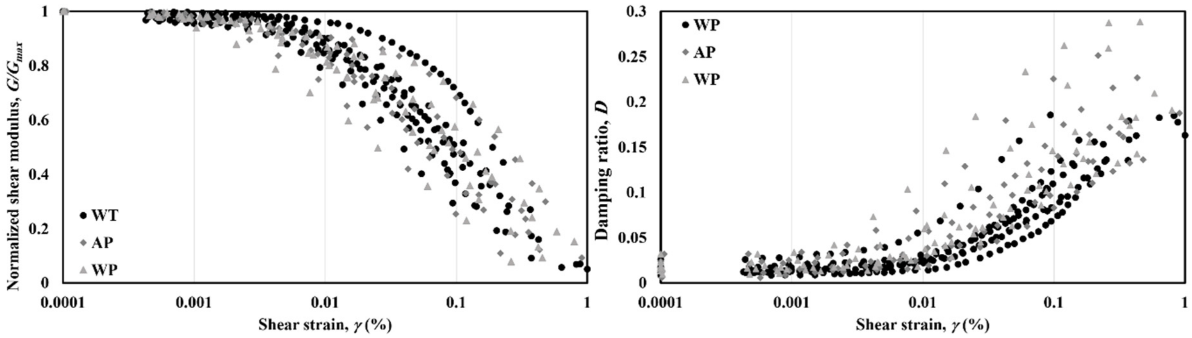

Fig. 5 Variation of G/G_{max} and D as a function of γ in terms of depositional methods.

4.2. EFFECT OF INDUCED ANISOTROPY ON $G/G_{max} - \gamma$ AND $D - \gamma$ CURVES

Group 2 of the tests was performed on the all subgroups under anisotropic conditions at different values of σ'_m. All specimens were prepared to a constant D_r of about 60 % that refers to the density after the consolidation stage. The aim of group 2 testing was to examine the effect of induced anisotropy on dynamic properties. The consolidation stress ratio ($K_C = \sigma'_l/\sigma'_a$) can be used to describe induced anisotropy, where σ'_l and σ'_a are the lateral and axial effective consolidation stress, respectively. The effect of K_C on the G/G_{max} - γ and D - γ curves for all subgroups is presented in Figure 4. In general, an increase in K_C tends to decrease G/G_{max} and increased D. More details about the effect of K_C on the dynamic properties can be found in Bayat and Ghalandarzadeh (2020).

4.3. EFFECT OF INHERENT ANISOTROPY ON $G/G_{max} - \gamma$ AND $D - \gamma$ CURVES

Group 3 of the tests was performed on saturated specimens of three subgroups (GC=0, 50 and 100) by three distinctive methods of specimen preparation, namely, WT, WP and AP. The primary objective of the group 3 of the tests was to evaluate the effect of inherent anisotropy on the dynamic properties of granular soil. The G/G_{max}-γ and D-γ curves of the specimens prepared using three methods are presented in Figure 5. The results show that the G/G_{max}-γ curves for the WT specimens goes slightly lower than those of the WS and AP specimens and also the D-γ curves for the WT specimens goes slightly lower than those of the AP and WS specimens for a given soil type. More details about the effect of specimen preparation methods on the dynamic properties is also discussed in Bayat and Ghalandarzadeh (2019).

5. THE PROPOSED MODELS

The effect of grading characteristics, inherent and induced anisotropy can be added to the general G_{max} expression as follows:

$$G_{max} = c_{sp} \times a_1 \times C_u^{\left[a_2 - \frac{D_{50}}{100}\right]} \times \left(\frac{\sigma'_m}{101}\right)^{a_3} \times \frac{(a_4 - e)^2}{a_5 + e} \times \left(\frac{1}{K_C}\right)^{a_6} \quad (1)$$

where c_{sp} is a coefficient reflecting the effect of soil fabric or specimen preparation method. In the current study, c_{sp} for the specimens were prepared by WT, WP and AP are considered equal to 1.2, 1.1 and 1, respectively. C_u and D_{50} are coefficient of uniformity and mean grain-size (in mm), respectively. σ'_m is the mean effective confining pressure (in kPa) which can be defined as a function of σ'_3 and K_C ($\sigma'_m = \left[\sigma_3\left(2K_C + 1\right)\right]/3K_C$). Parameters a_1 to a_6 are fitting parameters reflecting the effect of particle shape and roughness. As shown in Table 3, a_1 to a_6 are constant for all subgroups. In the current study, the nonlinear least squares method was used for the identification of the model's parameters. In other words, the parameters were determined in such a way that the sum of the squares of the difference between

Table 3 The models parameters for soils.

Model parameters	CG=0 %, GC=30 %, GC=50 %, GC=75 % and GC=100 % (Current study)
a_1	195
a_2	0.03
a_3	0.55
a_4	2.97
a_5	14.09
a_6	0.18
b_1	0.05
b_2	0.55
b_3	0.009
b_4	0.03
c_1	1.03
c_2	1.016
d_1	0.03
d_2	-0.09
d_3	-0.30
e_1	0.10
e_2	0.30
e_3	0.20

a predicted value and the corresponding measured data can be minimized. The parameters were determined by minimizing the respective error using the Solver add- in with Microsoft Excel. K_C is the consolidation stress ratio that, as mentioned before, is the lateral to axial effective consolidation stress ratio and *e* is the void ratio. Figure 6 shows the comparison between the measured and predicted values of the G_{max} for the all subgroup materials. The predicted values of G_{max} are mostly within ±25 % of the measured values and R^2 (correlation coefficient) and RMSE (Root Mean Square Error) are obtained as 0.8623 and 23.4, respectively. As shown in Figure 6, the estimated values of G_{max} are mostly within ±25 % of the measured values. This validates the feasibility of the presented model to predict G_{max} under different conditions.

Previous studies indicated that the value of γ_r (i.e. the shear strain corresponding to G/G_{max}=0.5) very significantly affected by the specimen preparation method, the grading characteristics, the mean effective confining pressure and the void ratio and vary less significantly with the induced anisotropy (Bayat and Ghalandarzadeh, 2018, 2019 and 2020; Zhou et al., 2017; Xu et al., 2019). Similar to Eq. (1), the following relationship is assumed for γ_r:

$$\gamma_r = C_{sp} \times b_1 \times C_u^{\left[\frac{D_{50}}{100}\right]} \times \left(\frac{\sigma'_m}{101}\right)^{b_2} \times \frac{(b_3 - e)^2}{b_4 + e} \quad (2)$$

where b_1 to b_4 are the fitting parameters which dependent on the shape property and physical parameters of the granular material. Same as before the fitting parameters are constant for all subgroups, which are presented in Table 3.

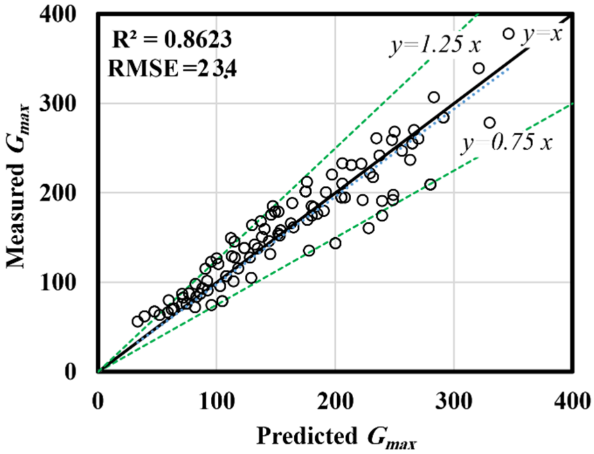

Fig. 6 G_{max}-values predicted by Eq. (1) versus measured G_{max} -values in the current study.

In the current study, a relatively simple modified hyperbolic model is used to predict the G/G_{max} as a function of (γ/γ_r). After the γ_r values are calculated based on Eq. (2), the G/G_{max} of the materials can be predicted using the following equation:

$$\frac{G}{G_{max}} = f\left(\frac{\gamma}{\gamma_r}\right) = \frac{1}{\left[1 + \left(\frac{\gamma}{\gamma_r}\right)^{c_1}\right]^{c_2}} \quad (3)$$

where c_1 and c_2 are the fitting parameters which are constant for all the subgroups as shown in Table 3. As shown in Figure 7, the correlation coefficient between the measured and predicted values of G/G_{max} and RMSE are 0.93 and 0.03, which validates the feasibility of this model. As can be seen in the results, the estimated values of G/G_{max} are mostly within ±30 % of the measured values.

Small strain damping ratio, D_{min}, of soil are one of the key input parameters in seismic analysis of the ground. Santamarina and Cascante, (1998) indicated that D_{min} is not influenced by the void ratio.

The results of the current study indicate that the main factors affecting the D_{min} are the mean effective confining pressure, void ratio and soil grading characteristics. The following empirical equation is used to estimate the D_{min}:

$$D_{min} = d_1 \times C_u^{d_2} \times \left(\frac{\sigma'_m}{101}\right)^{d_3} \quad (4)$$

where d_1 to d_3 are the fitting parameters which are constant for all the subgroups as shown in Table 3. As shown in Figure 8, the proposed equation predicts values relatively well at desired distribution around $y=x$ line and the estimated values of D_{min} are mostly within ±33 % of the measured values.

In the current study, the D-D_{min} is also expressed in terms of a polynomial function of G/G_{max} which has

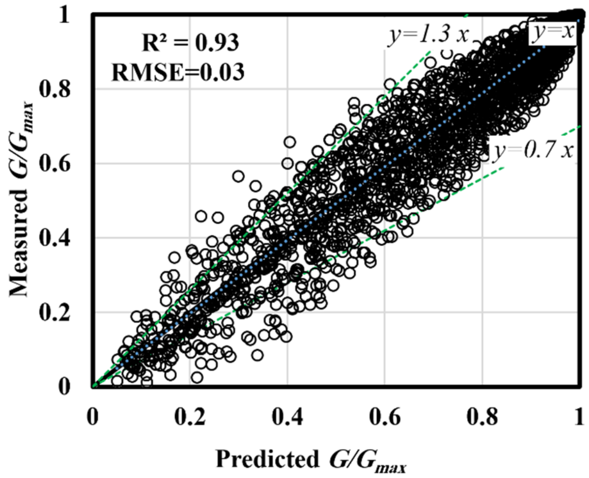

Fig. 7 G/G_{max}-values predicted by Eq. (3) versus measured G/G_{max} -values in the current study.

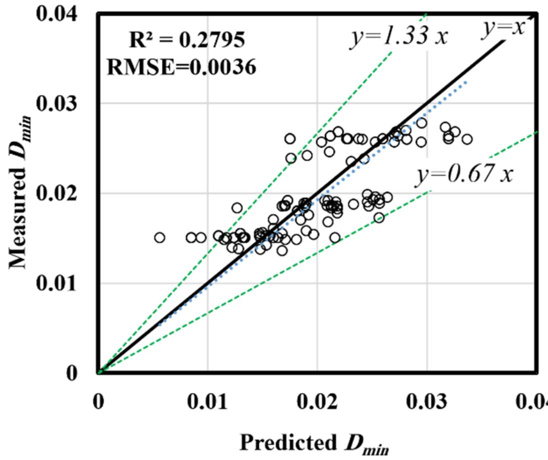

Fig. 8 D_{min} -values predicted by Eq. (4) versus measured D_{min} -values in the current study.

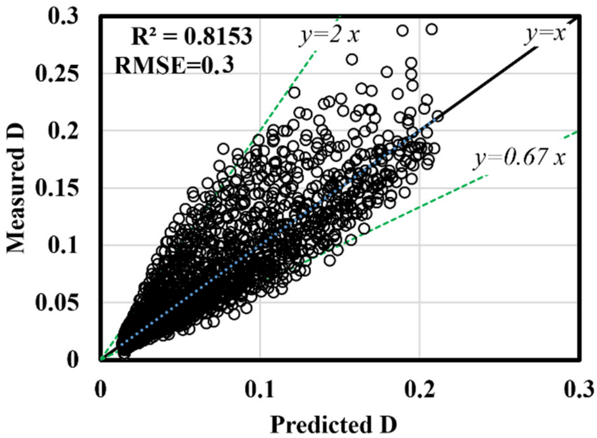

Fig. 9 D-values predicted by Eq. (5) versus measured D-values in the current study.

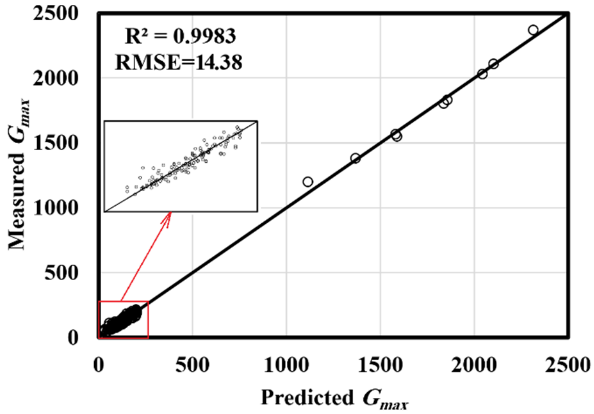

Fig. 10 G_{max}-values predicted by Eq. (1) versus measured G_{max} -values in the previous studies.

already been used by Wichtmann and Triantafyllidis (2012) and Zhang et al. (2005):

$$D - D_{min} = f(\frac{G}{G_{max}}) \rightarrow D = D_{min} + e_1(\frac{G}{G_{max}})^2 + e_2(\frac{G}{G_{max}}) + e_3 \quad (5)$$

where e_1 to e_3 are fitting parameters in which $e_1 + e_2 + e_3 \approx 0$ so that for very small shear strains $D=D_{min}$. e_1, e_2 and e_3 values are presented in Table 3 for all the subgroups. It should be noted that the values of G/G_{max} and D_{min} in Eq. (5) are calculated from Eqs. (3) and (4), respectively. As shown in Figure 9, the correlation coefficient between the measured and predicted values of D and RMSE are 0.8153 and 0.3, which indicate that the proposed equation predicts values that are close to the measured ones.

6. VALIDATION OF THE PROPOSED MODELS WITH PREVIOUS STUDIES

The data from Chen et al. (2018), Zhou et al. (2017) and Youn et al. (2008) were used to validate the ability of the proposed model to predict G_{max}. Table 4 summarizes the sources of data used in validating the model (digitization of the test data was undertaken) and the corresponding values of R^2 and RMSE. The best-fit values of the models' parameters for each test group are also listed in Table 4. Figure 10 shows the predicted versus measured values of G_{max}. The values of RMSE and R^2 of the model for all data has been illustrated numerically in Figure 10. As shown, the values of RMSE error and R^2 between the measured and predicted values is 14.38 and 0.9983, respectively, which validates the feasibility of the proposed model.

The data from Chen (2017), Zhou et al. (2017), Javdanian and Jafarian (2012), Araei et al. (2010), Youn et al. (2008) and Kokusho (1980) were used to validate the ability of the proposed models to predict the normalized shear modulus and damping ratio of granular soils over a wide shear strain range (0.0001 % to 10 %). The data were derived from various papers which contains various types of soils tested under

Table 4 Summarizes the sources of data used in verifying the proposed model of G_{max} and the corresponding model parameters.

Model parameters	Youn et al. (2008)	Youn et al. (2008)	Zhou et al. (2017)	Chen et al. (2018)	Chen et al. (2018)	Chen et al. (2018)
Materials	Silica sand	Toyoura sand	HZY-1	AGS-1 to AGS-5	AGS-6 to AGS-12	SGS-1 to SGS-7
a_1	218	183	235	244	240	176
a_2	3.30	12.30	1.49	0.46	0.14	0.28
a_3	0.43	0.45	0.38	0.53	0.39	0.46
a_4	1.26	1.59	2.46	2.78	4.03	3.38
a_5	6.47	33.55	45.75	77.74	70.97	66.80
a_6	1	1	0.25	0.35	0.22	0.01
R^2	0.99	0.99	0.98	0.81	0.88	0.88
RMSE	1.13	2.01	40.08	16.05	13.43	16.01

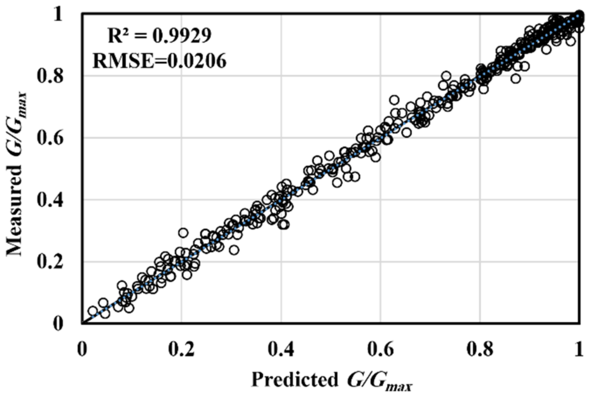

Fig. 11 G/G_{max}-values predicted by Eq. (3) versus measured G/G_{max} -values in the previous studies.

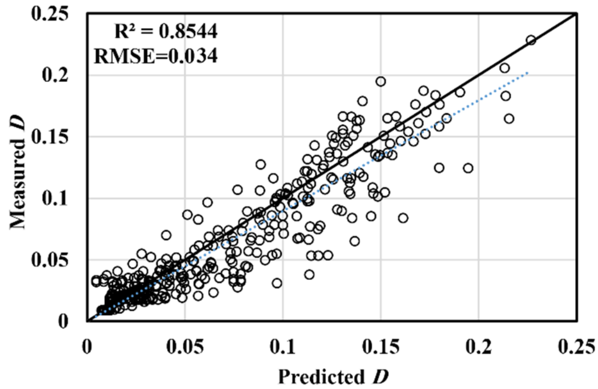

Fig. 12 D -values predicted by Eq. (4) versus measured D -values in the previous studies.

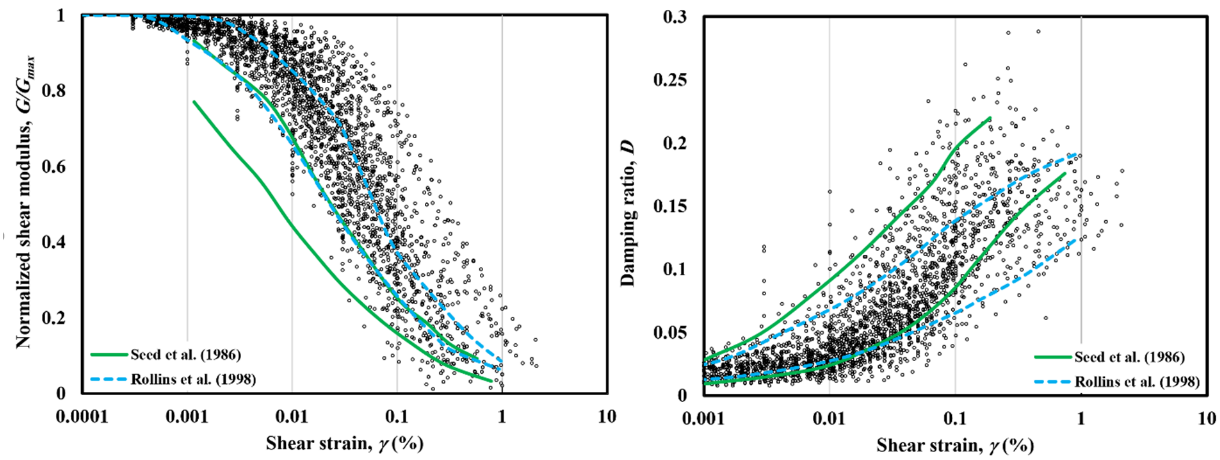

Fig. 13 G/G_{max} and $D-\gamma$ data points along with recommended the lower and upper curves developed by Seed et al. (1986) and Rollins et al. (1998).

a variety of conditions. Table 5 summarizes the sources of data, properties of the specimens and testing conditions that were reported in the original publications. The best-fit values of the models parameters for each test group are also listed in Table 5. Figueres 11 and 12 shows the predicted versus measured values of G/G_{max} and D for the 34 tests detailed in Table 5, respectively. As shown in Figures 11 and 12, the values of R^2 is 0.9929 and 0.8544 for $G/G_{max}-\gamma$ and $D-\gamma$ curves, respectively, which verifies the feasibility of the proposed models.

All the results in this study and used results of previous studies along with the upper and lower curves of $G/G_{max}-\gamma$ and $D-\gamma$ as reported by Seed et al.

Table 5 Summarizes the sources of data used in verifying the proposed models of G/G_{max} and D and the corresponding model parameters.

Publication	**Materials type**	**Materials symbol**	***Soil properties***			**Confining Stress (kPa)**	***K***	***Models parameters***											
			D_{50} **(mm)**	C_u	e_0			b_1	b_2	b_3	b_4	c_1	c_2	d_1	d_2	d_3	e_1	e_2	e_3
Chen et al. (2018)	Angular sand-gravel mixture					100	0.4												
		AGS 7	1.6	18.18	0.736	100	0.67												
						100	1												
						100	1	1.39	0.47	0.10	0.10	0.81	2.53	0.001	0.127	0.014	0.01	0.17	0.17
						300	1												
		AGS 11	5.65	41.45	0.477	500	1												
						700	1												
						900	1												
Zhou et al. (2017)	Rockfill materials	HZY-1	17.34	7.52	**0.235**	1000	0.67												
						2000	0.4												
		HZY-2	14.2	30.25	**0.195**	2000	0.4												
						3000	0.67												
		HZY-3	7.85	85.29	**0.205**	1000	0.67	0.01	0.31	0.71	1.92	1.05	0.33	0.021	0.001	0.001	0.18	0.36	0.19
						3000	0.67												
		HZY-4	17.34	7.52	**0.235**	1000	0.67												
						2000	0.4												
		HZY-5	17.34	17.76	**0.179**	2000	0.4												
						3000	0.67												
Araei et al. (2010)	Rockfill materials	S-3BMES	10.743	652.40	**0.28**	700	1												
						200	1												
		S-3AMES	4.114	139.10	**0.281**	700	1												
						200	1												
		S-SC	4.100	95.53	**0.227**	800	1	0.01	0.44	1.75	1.67	0.82	1.00	0.031	0.001	0.007	0.10	0.27	0.17
						200	1												
						500	1												
		S-SK	4.166	142.60	**0.335**	500	1												
						300	1												
Javdanian and Jafarian (2012)	Babolsar sand	BSS	0.35	3.43	**0.53**	800	1												
						400	1	1.40	0.44	0.72	0.90	0.99	1.45	0.006	0.386	0.001	0.10	0.20	0.10
						200	1												
Kokusho (1980)	Toyoura sand	T	0.198	1.34	**0.643**	300	1												
						200	1												
						100	1	1.38	0.49	1.28	1.40	0.72	2.00	0.011	0.572	0.054	0.15	0.42	0.27
						50	1												
						20	1												

(1986) and Rollins et al. (1998) are shown in Figure 13. As seen, the measured G/G_{max} values completely fall above the upper bound trend reported by Seed et al. (1986). The lower curve of Rollins et al. (1998) in the range $\gamma < 0.02$ % fall below the data; however, the upper range of Rollins et al. (1998) is significantly different compared to the upper range of data. It appears that the upper and lower curves of $D - \gamma$ developed by Seed and Idriss (1986) and Rollins et al. (1998) provide good prediction of damping ratios of granular soils.

7. CONCLUSIONS

Previous studies that analyzed dynamic properties of granular soils have most often used different functional forms of models to predict the data which were proposed for specific soil types, loading characteristics, initial soil fabrics and strain ranges. This paper describes the development of universal models to estimate dynamic properties for granular soils from soil grading characteristics, loading conditions and the structure or fabric of the soil. Three models (Eqs. (1), (2) and (4)) have been developed to predict G_{max}, D_{min} and γ_r from a collected database that contains 117 tests. Second, two models (Eqs. (3) and (5)) are presented to estimate G/G_{max} and D from G_{max}, D_{min} and γ_r. The results of the tests indicate that the G_{max} of granular soils is affected by the grading characteristics, the mean effective confining pressure, the void ratio, the soil fabric, and the consolidation stress ratio. The experimental results exhibit that the G_{max} increases with increasing mean effective confining pressure and decreases with increasing void ratio or the consolidation stress ratio. As shown in the results, γ_r can be defined as a function of the grading characteristics, the mean effective confining pressure, the void ratio and the soil fabric which increases with increasing mean effective confining pressure and decreases with increasing void ratio. The tests result show that γ_r is almost independent of the consolidation stress ratio. Based on the tests results, D_{min} is defined as a function of grading characteristics and mean effective confining pressure, so that it decreases with increasing uniformity coefficient and mean effective confining pressure. In this work, a relatively simple modified hyperbolic model is used to predict the G/G_{max} as a function of (γ/γ_r) and the D-D_{min} is also expressed in terms of a polynomial function of G/G_{max}. The presented models to estimate $G/G_{max} - \gamma$ and $D - \gamma$ curves cover a complete range of shear strains and were evaluated against different granular soil types, unlike many of previous models that are valid only for limited ranges of shear strains and provided for a given soil type. The models are validated using experimental data from previous studies for granular soils. The results indicate that the proposed models are capable of evaluating the dynamic properties of granular soils and are sufficiently flexible to be used for any granular soil types. The results also indicate that fitting parameters dependent on shape property and physical parameters of granular material and are independent of grading characteristics. Tables 3 to 5 lists fitting parameters of the proposed models.

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